

Galaxy formation and evolution since $z=1$

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Abstract. Determination of the star formation rate can be done using mid-IR photometry or Balmer line luminosity after a proper correction for extinction effects. Both methods show convergent results while those based on UV or on [OII] λ 3727 luminosities underestimate the SFR by factors ranging from 5 to 40 for starbursts and for luminous IR galaxies, respectively. Most of the evolution of the cosmic star formation density is related to the evolution of luminous compact galaxies and to luminous IR galaxies. Because they were metal deficient and were forming stars at very high rates (40 to 100 $M_{\odot} yr^{-1}$), it is probable that these (massive) galaxies were actively forming the bulk of their stellar/metal content at $z \leq 1$.

1 Introduction

Determining how galaxies formed and grew is one of the outstanding problems of modern astrophysics. The epoch at which half the stellar mass was formed has been estimated to be $z=1-1.5$ from simple integrations of the global star formation history of the Universe ([1]; [2]). Similar results have been found by estimating the growth of galaxies by calculating the stellar mass from SEDs with broad wavelength coverage ([3]; [4]; [5]). However, this method depends strongly on the estimated M/L of individual galaxies which is sensitive to the assumptions about their star formation history, dust distribution, metallicity, and IMF – all of which are usually poorly constrained. Many efforts have been made to study galaxies at redshifts higher than 1, in attempts to track the formation of half the present day stellar mass. However the situation at $z > 1$ is difficult, because of their faintness and because most of the important lines for diagnostics are redshifted to the near IR. Here we choose to investigate the properties of $z \leq 1$ galaxies, for which the current generation of telescopes is able to provide accurate measurements of their properties (star formation rates, masses, metal abundances). In a cosmological model with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-3}$, $\Omega_A = 0.7$ and $\Omega_M = 0.3$, $z=1$ corresponds to 58% of the Universe age. At $z > 0.4$, the emergence of two galaxy populations have been reported, namely the luminous infrared galaxies (LIRGs, [1]; [6]) and the luminous compact galaxies (LCGs, [7]; [8]). These two populations are responsible of most of the evolution of the IR and UV luminosity density evolutions, and then of a significant fraction of the cosmic star formation density at $z \sim 1$.

In the following, we present a summary of results based on follow-up studies of the Canada France Redshift Survey (CFRS) using the Very Large Telescope

(VLT), the Infrared Space Observatory (ISO) and the Hubble Space Telescope (HST).

2 Estimating extinction and SFR at $z \sim 1$

A prerequisite for estimating star formation from emission is to properly estimate the extinction. $H\alpha$ luminosity is one of the best indicator of the instantaneous SFR. However low resolution spectroscopy ($R < 500$) often produces misleading results [9]. Only good S/N spectroscopy with moderate spectral resolution ($R > 600$) allows a proper estimate of the extinction from the $H\alpha/H\beta$ ratio after accounting for underlying stellar absorption. SFRs can be otherwise underestimated or overestimated by factors reaching 10, even if one accounts for an *ad hoc* extinction correction. These effects are prominent for a large fraction of evolved massive galaxies especially those experiencing successive bursts (A and F stars dominating their absorption spectra). Further estimates of the cosmic star formation density at all redshifts mandatorily requires moderate resolution spectroscopy to avoid severe and uncontrolled biases.

Liang et al ([9]) have given an obvious warning for the studies based on low resolution spectroscopy aimed at measuring individual galaxy properties (gas chemical abundances, interstellar extinction, stellar population, ages as well as star formation rates and history), particularly for dusty spiral galaxies. For example, it has been shown ([10]) that 1/4 of the Lilly et al sample ([11]) of $z \sim 0.7$ galaxies was made of LIRGs which are dust enshrouded systems (average $A_V = 2.4$). Assuming a constant extinction of $A_V = 1$ for these LIRGs, leads to underestimate their $[\text{OII}]\lambda 3727/H\beta$ ratio, providing an overestimate of their metallicity by 0.3 to 0.5 dex.

ISOCAM observations give us a unique opportunity to test the validity of our SFR estimates. It has been shown ([6], see also David Elbaz's contribution) that the mid-IR and radio luminosities correlate well up to $z=1$. Bolometric IR measurements derived from mid-IR are validated, unless if both the radio-FIR and the MIR-FIR correlations are invalid at high redshifts. Mid-IR photometry provides an unique tool to estimate properly the SFR of LIRGs (defined as $L_{IR} > 2 \cdot 10^{11} L_\odot$) up to $z=1.2$, and of starbursts ($L_{IR} < 2 \cdot 10^{11} L_\odot$) up to $z=0.4$. For a sample of 16 ISO galaxies at $0 < z < 1$, SFRs have been derived from the extinction corrected $H\alpha$ luminosities ([12]). These values agree within a factor 2 with mid-IR estimates (median value of $SFR_{IR}/SFR_{H\alpha} = 1.05$). Using moderate spectral resolution ($R = 1200$) with good S/N of 90 ISO galaxies ($0.2 < z < 1$), Liang et al [10] have shown that the extinction can be properly derived from the $H\beta/H\gamma$ ratio. Such measurements can be performed for all galaxies up to $z=1$ within an accuracy of 0.6 mag for A_V values, and then for SFR values.

It has been argued ([13]) that the $[\text{OII}]\lambda 3727$ luminosity can provide an efficient way to derive SFRs of high redshift galaxies using spectrographs in the visible range. However preliminary results from [14] and [15] have shown that the correlation between $H\alpha$ and $[\text{OII}]\lambda 3727$ is rather poor, because of extinction effects and also because it considerably depends on the galaxy metallicity,

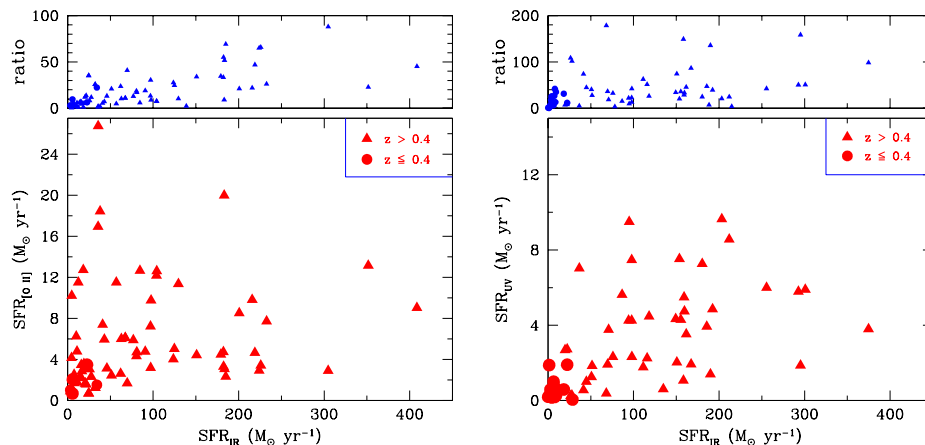


Fig. 1. Comparison of SFRs calculated using the formalism of [13]. (*Left panel*): [OII] λ 3727 estimates are compared to IR estimates for a sample of 70 galaxies from the CFRS and Marano fields (see [10]). [OII] λ 3727 estimates have been done using the formulae from [7] which have been adequately multiplied by 2.46 to account for the fact that they have used a different IMF than [13]. Upper left panel provides the $SFR_{IR}/SFR_{[OII]}$ ratio. Median values of the ratio are 5 and 22 for starbursts ($SFR < 40 M_{\odot} yr^{-1}$) and LIRGs respectively. (*Right panel*): same comparison for UV (2800Å) luminosity estimated for 61 CFRS galaxies. Median values of the SFR_{IR}/SFR_{UV} ratio are 13 and 36 for starbursts ($SFR < 40 M_{\odot} yr^{-1}$) and LIRGs, respectively.

luminosity and spectrophotometric type. How [OII] λ 3727 estimates compare to IR (or $H\alpha$) estimates of the SFR? Figure 1 shows that the former strongly underestimates the SFR by factor 5 for starbursts and factor 22 for LIRGs. A similar result is found by comparing SFR estimates from UV to those from IR, and has been already discussed by [8] for a sample of distant LCGs (average $SFR = 40 M_{\odot} yr^{-1}$). The fact that UV fluxes provide even lower SFR values than [OII] λ 3727 fluxes might be related to the expected increase of [OII] λ 3727/ $H\beta$ ratio with decreasing metal abundance (high z systems being expected to be less metal abundant than local ones).

3 Were all massive galaxies already formed at $z=1$?

It has been claimed ([16]) that the stellar mass built up of massive spirals was mostly done at $z \sim 1$. This claim was based on the very low values of the $SFR/M_{stellar}$ for CFRS galaxies, yielding very low stellar mass increases (ranging from 1 to 10%) for massive galaxies ($M_{stellar} > 10^{11} M_{\odot}$) since $z=1$. If true, this result would imply that most of the star formation at $z < 1$ occurred in dwarf galaxies. However, present day dwarves contain only a marginal fraction of the stars or metals, and the Brinchman and Ellis's result ([16]) is somewhat at odd with integrations of the star formation history and with stellar mass density at

different lookback times. We notice that SFRs calculated by [16] were based on the formulae from [7], and provide values 54 and 12 times lower than our estimates for LIRGs and starbursts, respectively. This potentially leads to a severe revision of the conclusions from [16].

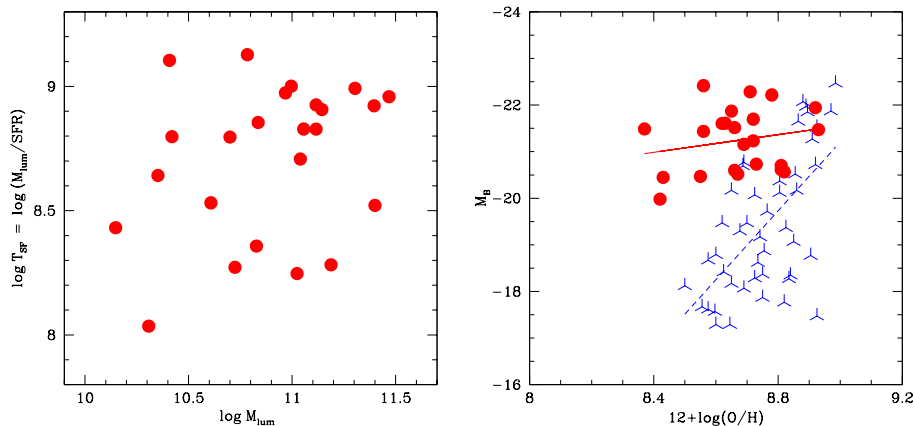


Fig. 2. (*Left panel*): M_{stellar}/SFR against M_{stellar} for distant LIRGs (from [17]). Because of their very high SFRs, LIRGs can build up of significant part of their masses in relatively short times. (*Right panel*): M_B versus O/H abundance ratio of distant LIRGs (from [10], full dots) compared to those of local spirals (from [18] and [15], skeletal symbols). Full line and dotted lines report the regression law for LIRGs and local spirals, respectively. At $z \sim 0.75$, LIRGs have $\log(O/H)$ values 0.3 dex lower than those of local spirals.

A pioneering study of 14 distant LCGs ($M_B < -20$; $r_{\text{half}} \leq 3.5 h_{70}^{-1}$ kpc) have revealed that they are dust enshrouded starbursts superimposed to an old and evolved stellar population. It has lead us ([8]) to suggest that LCGs are the progenitors of present-day spiral bulges, prior to the star formation in the disk component. Because LCGs correspond to 23% of the luminous galaxy population at $z \sim 0.75$, they could be the progenitors of a similar fraction of present-day luminous spirals.

Recently, important progress has been made in our understanding of distant LIRGS ([10]; [17]). They are forming rapidly new generations of stars and possess stellar masses comparable or slightly smaller than that of present-day massive spirals (Figure 2; [17]). Galaxies experiencing such strong star forming events could form a significant fraction of their masses during the last 8 Gyr. Their metal content have been found to be on average half that of today massive spirals (Figure 2; [10]): at such rates of star/metal production, they can be the progenitors of massive spirals within timescales much smaller than a Hubble time. Indeed LIRG morphologies are intimately related to giant disks (Figure 3;

[17]), and, incidentally include a significant fraction of compact galaxies. Because LIRGs and LCGs are much more frequent at $z > 0.4$ than today, a substantial fraction of massive galaxies could be actively forming their stellar content at $z < 1$. It does not necessarily contradict previous studies (e.g. [19]) which have shown that the number density of large spirals ($r_{\text{disk}} > 2.8 h_{70}^{-1}$ kpc) was similar at $z=0.75$ than today. In fact we realize that one third of the large disks in the sample of [19] were indeed LIRGs, strengthening our prediction that many large spirals were actively forming the bulk of their stellar content at $z < 1$.

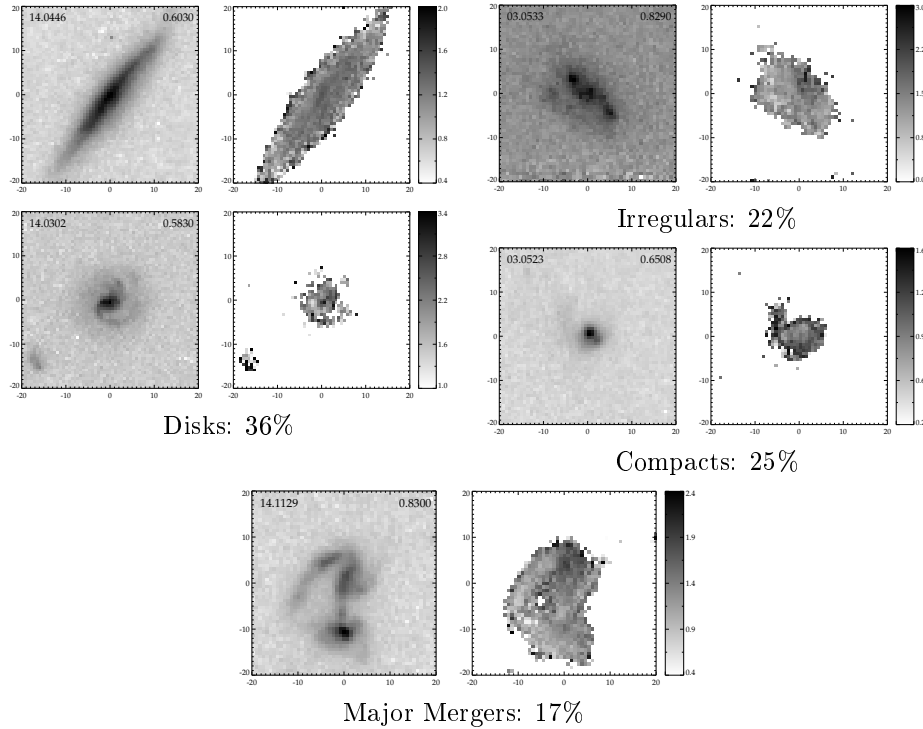


Fig. 3. Morphological classifications using color maps from a study of 36 LIRGs by [17]. Using color map and deconvolution software (GIM2D), it has succeeded to classify all the galaxies (fractions of each type are given). For each galaxy, the left stamp (40x40 kpc^2 area) shows the F814W WFPC2 image, and the right stamp shows the color map (F606W-F814W) following the prescription of Zheng et al ([17]). Color map have been derived after a very accurate alignment of V and I images down to 0.015 arcsec, which is a prerequisite for galaxies with some irregularities in their morphologies. Notice the fact that most distant galaxies show small blue and very red regions, interpreted as HII regions and dusty enshrouded regions, respectively. Notice also the very blue color in the center of compact galaxies.

Extragalactic studies might appear inaccurate and affected by numerous biases and uncertainties when compared to WMAP results (see Licia Verde's contribution): they have been nicknamed "dirty physics" during the first talk of the Conference. Indeed, the extensive use of photometric redshifts or of low resolution spectroscopy of $z > 1$ galaxies can cast some doubts about our knowledge of their properties. On the other hand, physical parameters of $z \leq 1$ galaxies can be determined rather accurately, because these sources are enough bright to be at the reach of current telescopes. This requires to apply methodologies (for example high S/N and medium resolution spectroscopy) which have been successful for analysing local galaxy properties. In this paper, we also systematically compare two independent estimates of each individual parameter: SFR calculations have been done by comparing IR and Balmer line luminosities and stellar production in LIRGs and in LCGs have been compared to their metal content relative to that of local spirals.

We intend to pursue our analyses towards the general population of field galaxies up to $z=1$, including by studying their morphologies, metal content and SFRs (Hammer et al, 2004, in preparation). We believe that establishing a new classification sequence for all galaxies at $z < 1$ is at the reach of the present generation of telescopes. An important goal will be to study their dynamics using the multi-integral field unit mode of FLAMES/GIRAFFE at VLT. It would provide an important test for the merging scenario, as well as a solid estimate of the evolution of the Tully-Fisher relation up to $z=1$. Dynamical masses of galaxies could be then compared to their stellar masses.

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